The Properties of Ultraviolet-Luminous Galaxies at the Current Epoch

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ABSTRACT

We have used the first matched set of GALEX and Sloan Digital Sky Survey (SDSS) data to investigate the properties of a sample of 74 nearby ($z < 0.3$) galaxies with far-ultraviolet luminosities greater than $2 \times 10^{10} L_{\odot}$, chosen to overlap the luminosity range of typical high-z Lyman Break Galaxies (LBGs). GALEX deep surveys have shown that ultraviolet-luminous galaxies (UVLGs) similar to these are the fastest evolving component of the UV galaxy population. Model fits to the combined GALEX and SDSS photometry yield typical FUV

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extinctions in UVLGs of 0.5 to 2 magnitudes (similar to LBGs and to less luminous GALEX-selected galaxies). The implied star formation rates are SFR $\sim$ 3 to 30 $M_\odot$/year. This overlaps the range of SFRs for LBGs. We find a strong inverse correlation between galaxy mass and far-ultraviolet surface brightness, and on this basis divide the sample into "large" and "compact" UVLGs. The large UVLGs are relatively massive ($M_* \sim 10^{11} M_\odot$) late type disk galaxies forming stars at a rate similar to their past average ($M_*/SFR \sim t_{Hubble}$). They are metal rich ($\sim$ solar), have intermediate optical-UV colors ($FUV - r \sim 2$ to 3), and about a third host a Type 2 (obscured) Active Galactic Nucleus. In contrast, the compact UVLGs have half-light radii of a few kpc or less (similar to LBGs). They are relatively low-mass galaxies ($M_* \sim 10^{10} M_\odot$) with typical velocity dispersions of 60 to 150 km/s. They span a range in metallicity from $\sim$ 0.3 to 1 times solar, have blue optical-UV colors ($FUV - r \sim 0.5$ to 2), and are forming stars at a rate sufficient to build the present galaxy in $\sim$1 - 2 Gigayear. In all these respects they appear similar to the LBG population. These "living fossils" may therefore provide an opportunity for detailed investigation of the physical processes occurring in typical star forming galaxies in the early universe.

Subject headings: Galaxies: general — Galaxies: evolution — Galaxies: starburst — Ultraviolet: galaxies

1. Introduction

Over the past several years the first picture of the cosmic evolution of the global star-formation rate has been sketched (e.g. Giavalisco et al. 2004; Dickinson et al. 2003). This is a truly remarkable achievement. However, there is considerable work to be done. The ultimate goal of course is to understand the astrophysical processes that drove the evolution of star formation and to relate these processes to the building of galaxies, the fueling of active galactic nuclei, and the development of large-scale structure. This will require detailed and statistically robust comparisons of the fundamental properties of star forming galaxies as a function of redshift.

One obstacle has been that our understanding of the evolution of star formation has until recently been a patchwork quilt that relied on different techniques (each with their own selection biases and systematic methodological uncertainties) over different redshift ranges. For example, our most detailed information about star formation in the early universe has been provided by the large sample of (rest-frame) UV-selected Lyman Break Galaxies (LBGs). Ironically, the properties of the UV-selected galaxy population have been much more fully characterized at z $\sim$ 3 than at $z \sim 0$ (e.g. Shapley et al. 2001; Papovich et al. 2001; Giavalisco 2002 - hereafter S01, P01, and G02 respectively).

This situation has changed dramatically with the successful launch of the *Galaxy Evolution Explorer* (GALEX). Its All-sky Imaging Survey (AIS) and Medium Imaging Survey (MIS) will generate UV-selected samples of a million relatively nearby star forming galaxies (Martin et al 2004) with optical photometry and spectroscopy from the Sloan Digital Sky Survey (SDSS - York et al. 2000).

One of the first major results from the GALEX mission is the measurement of the evolution of the galaxy ultraviolet luminosity function from $z \sim 0$ to 4 (Arnouts et al. 2004; Schiminovich et al., 2004). As emphasized in these papers, the rate of cosmic evolution in the ultraviolet galaxy population is strongest at the highest luminosities. In particular, the co-moving space density of galaxies with far-ultraviolet luminosities $L_{FUV} > 10^{10.1} L_{\odot}$ increases by a factor of $\sim$30 from $z = 0$ to 1, and by additional factor of $\sim$4 out to $z = 3$.

Thus, it is clearly important to identify and study the most ultraviolet- luminous galaxies in the relatively nearby universe, and then compare the properties of these (rare) objects to their counterparts at high-redshift (most notably, the LBGs). In the present paper we use the results from the initial matching of the GALEX and SDSS data to initiate such an investigation.

2. Sample Selection and Data Description

Our goal is to define a sample of local galaxies that overlap significantly in UV luminosity with LBGs. However, within this range, the number of local galaxies is falling very steeply with luminosity. For this reason, we have chosen to define a sample of "Ultraviolet Luminous Galaxies" (UVLGs) as having FUV luminosities (λP_{λ} at 1530 Å) $\geq 2 \times 10^{10} L_{\odot}$.[1] This defining luminosity is roughly half way between the characteristic (L_*) value for the present day UV galaxy luminosity function ($10^{9.6} L_{\odot}$ - Wyder et al. 2004) and that of the LBG population at $z \sim 3$ ($10^{10.8} L_{\odot}$ - G02; Arnouts et al. 2004).

We started by matching the GALEX IR0.2 and SDSS Data Release One catalogs (as detailed in Seibert et al. 2004). We then selected those objects spectroscopically classified as galaxies by the SDSS, specifically excluding objects spectroscopically classified QSOs (or Type 1 Seyfert galaxies). Finally, we have inspected the spectra and removed a few weak Type 1 AGN that had been misclassified by SDSS. This gives us a sample of 74 galaxies,

[1] We use H_0=70 km sec^{-1} Mpc^{-1}, Ω_m=0.3, and Ω_{Λ}=0.7 throughout this paper.

spread rather uniformly in redshift between 0.1 and 0.3 (median z = 0.19). These galaxies are indeed rare: the co-moving space density of UVLGs at the current epoch is only $\sim 10^{-5}$ Mpc^{-3}, several hundred times smaller than the co-moving density of LBG at z ∼3.

The SDSS data by themselves provide a host of important galaxy parameters (Abazajian et al. 2003; Stoughton et al. 2002). We have used the SDSS Data Release Two archive to retrieve the Petrosian magnitudes and seeing-deconvolved half-light radii in the u and r bands, the concentration index C in the r-band, and the redshift for all the UVLGs. For the UVLGs in the SDSS "main" galaxy sample (Strauss et al. 2002), we have used the value-added catalogs described at http://www.mpa-garching.mpg.de/SDSS/ to retrieve estimates of gas-phase metallicities, emission-line widths, age-sensitive 4000 Å break amplitudes, emission-line ratios, and classifications (AGN vs. star forming). See Kauffmann et al (2003a,b), Brinchmann et al. (2004), and Tremonti et al. (2004) for details. For the other UVLGs we have used the methodology described in Tremonti et al. (2004) to measure fluxes and widths of the emission-lines. The combined GALEX plus SDSS 7-band photometry has been used in conjunction with an extensive grid of models to estimate the stellar masses, FUV extinctions, and star formation rates. See Salim et al. (2004) for details. [2]

3. Results

3.1. Basic Structural Properties

In Figure 1 we show a plot of the far-UV luminosity L_{fuv} *vs.* the half-light radius in the SDSS u-band (R_u). [3] For the redshift range of the UVLGs, the SDSS u-band covers the rest-frame range ∼2700 to 3200Å band, where the contribution by young stars should dominate (given the high specific star formation rates discussed below). The UVLGs span a broad range in size, from relatively compact systems with radii of a kpc (similar to LBGs - Ferguson et al. 2004) to very large galaxies with radii of over 10 kpc. This implies a correspondingly large range in far-UV surface brightness (I_{fuv} - Figure 2). The UVLGs overlap the range of I_{fuv} of typical LBGs ($\sim 10^9$ to $10^{10} L_\odot$ kpc^{-2}), but most are significantly fainter. Figure 2

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[2] A table with the relevant SDSS and GALEX-derived parameters for the 74 sample galaxies is available at http://www.mpa-garching.mpg.de/SDSS/Data/uvlg.html

[3] We have used radii based on the best fitting seeing-convolved exponential disk models from the SDSS (see http://www.sdss.org/dr2/algorithms/photometry.html#mag_model). While these radii are therefore corrected in principle for the effects of seeing, it is important to note that the compact UVLGs are not well-resolved in the SDSS images. Thus, the radii and implied surface brightnesses of the compact UVLGs are relatively uncertain.

shows that there is a strong inverse correlation between surface brightness and mass.

While it is clear that a continuum of properties is present, the wide range of physical properties makes it instructive to subdivide our sample into two categories: "large" ($I_{fuv} < 10^8 L_\odot$ kpc^{-2}) and "compact" ($I_{fuv} > 10^8 L_\odot$ kpc^{-2}). This choice not only divides the sample into two subsets with roughly equal numbers, but it also divides the sample in galaxy mass at the critical value ($M_* \sim 10^{10.5} M_\odot$) where Kauffmann et al. (2003c) find that the SDSS galaxy population abruptly transitions from *primarily* low mass, low density, low concentration, disk dominated galaxies with young stellar populations to high mass, high density, high concentration, bulge dominated systems with old stellar populations.

The compact, high surface-brightness UVLGs are typically low-mass galaxies ($M_* \sim 10^{9.5}$ to $10^{10.7} M_\odot$). This mass range is very similar to that of LBGs (S01,P01,G02). These compact UVLGs are larger, more luminous, and more massive than local HII galaxies (Telles & Terlevich 1997) and overlap the high mass range of compact galaxies found at higher redshift ($0.4 \leq z \leq 1$) in the Hubble Deep Field (Phillips et. al 1997).

The large, low surface-brightness UVLGs are significantly more massive ($M_* \sim 10^{10.5}$ to $10^{11.3} M_\odot$). The high-mass galaxies in the SDSS that do have a significant population of young stars have the low concentrations typical of disk galaxies ($C < 2.6$), and this is the case for the large UVLGs (90 % of which have $C < 2.6$). The large UVLGs have typical values of effective stellar surface mass densities $\mu_* \sim 10^8$ to $10^{8.5} M_\odot$ kpc^{-2}. This is about a factor of three lower than average for comparably massive late type galaxies (see Figure 14 in Kauffmann et al 2003c). These UVLGs are corresponding larger than average late type galaxies of the same mass (Shen et al. 2003). These results are not surprising, since Kauffmann et al. (2003c) showed that at fixed galaxy mass, SDSS galaxies with lower μ_* (and thus larger radii) have younger stellar populations.

3.2. Star Formation Rates & Related Parameters

The typical values for the FUV extinction in UVLGs are modest: $A_{FUV} \sim 0.5$ to 2 magnitudes. This range is similar to that of a NUV-selected sample of galaxies that is representative of the local GALEX population (Buat et al. 2004), as well as that of LBGs (S01,P01). Adopting a Kroupa (2001) Initial Mass Function, the typical estimated star formation rates for the UVLGs are ~ 3 to 30 $M_\odot$ year^{-1} (or ~ 5 to 50 $M_\odot$ year^{-1} adopting the historically standard Salpeter Initial Mass Function). These star formation rates overlap the range spanned by LBGs (S01, P01, G02).

In Figure 3 we show that the *specific* star formation rate (SFR/M_*) is a strong function of the far-UV surface brightness. The compact, high surface brightness UVLGs have typical values of $SFR/M_* \sim 10^{-8.6}$ to $10^{-9.8}$ year^{-1}, compared to $\sim 10^{-9.5}$ to $10^{-10.5}$ year^{-1} for the large low surface brightness UVLGs. Of course the specific star formation rate is roughly the inverse of the time it would take to form the present galaxy mass at the present star formation rate. Thus, the large UVLGs are (in the mean) forming stars at a rate similar to their past rate averaged over a Hubble time. In contrast, the compact UVLGs have a typical "galaxy-building time" of only 1 to 2 Gigayear. Thus, they are "starburst" systems. The *most* compact UVLGs ($I_{fuv} \geq 10^9 L_\odot$ kpc^{-2}) have galaxy-building times of only 0.1 to 1 Gyr, very similar to the corresponding timescales in LBGs (S01,P01,G02).

Salim et al. (2004) and Brinchmann et al. (2004) have shown that the specific star formation rates in galaxies correlate strongly with the FUV-optical colors and the 4000 Å break amplitude (D4000), respectively. This is true for the UVLGs. The large UVLGs have intermediate colors ($FUV - r \sim 2$ to 3) and 4000 Å break strengths (D4000 $\sim$ 1.2. to 1.7), while the compact UVLGs have the blue colors ($FUV - r \sim 0.5$ to 2) and small 4000 Å break strengths (D4000 $\sim$ 1.0 to 1.3) of very young stellar populations (e.g. Kauffmann et al 2003a). The UV-optical colors of the compact UVLGs are very similar to those of LBGs (S01,P01,G02).

3.3. Chemical and Kinematic Properties

The metallicities in the ionized gas in the UVLGs are typical for SDSS galaxies of the corresponding stellar mass (Tremonti et al. 2004): the large (massive) UVLGs have oxygen abundances of several times solar, while the compact (less massive) UVLGs span a broad range in metallicity from $\sim$30% solar to several times solar. We note that the "strong-line" methods like those used by Tremonti et al. to estimate metallicity are known to yield systematically higher metallicities than direct techniques (Kennicutt, Bresolin, & Garnett 2003). Pettini & Pagel (2004) have recently recalibrated the "[OIII]/[NII]" strong line metallicity indicator. Using their calibration, the UVLG metallicities would be roughly solar for the large UVLGs and $\sim$30% solar to solar for the compact UVLGs. These latter metallicities are similar to estimates for LBGs (Pettini et al. 2001; Shapley et al. 2004).

Typical emission-line velocity dispersions range from 50 to 150 km sec^{-1}, with little dependence on galaxy mass. These are similar to values in LBGs (Pettini et al. 2001). Using these velocity dispersions and the u-band half-light radii we have computed dynamical masses ($M_{dyn} = 5\sigma_{gas}^2 R_u/G$). These agree with the stellar masses to within a typical factor of three.

3.4. Presence of Type 2 AGN

We have used the emission-line flux ratios [OIII]/Hβ vs. [NII]/Hα to identify UVLGs in which a type 2 AGN is making a significant contribution to the emission-line spectrum (see Kauffmann et al. 2003b). [4] We find that AGN are present in 35% of the large UVLGs, and in 15% of the compact UVLGs (the stronger emission lines produced by the more intense star formation makes the presence of an AGN more difficult to detect in the compact UVLGs). The great majority (83%) of the AGN would be classified by Kauffmann et al. as "Composite" systems in which the observed emission-lines are contributed by a combination of an AGN and O stars. The high rate of AGN in UVLGs is not surprising given the link between strong AGN and star formation in the population of massive galaxies in the SDSS (Kauffmann et al. 2003b).

4. Discussion & Conclusions

The large UVLGs have specific star formation rates sufficient to build their stellar mass over a Hubble time. Thus, they are not starburst systems. Instead they owe their high UV luminosities (high star formation rates) to their relatively large masses. These systems appear to be the tail of the distribution of the normal SDSS high-mass galaxy population, extending to high star formation rates, low stellar surface mass densities, large radii, low concentrations, and (by implication) high gas-mass fractions. That is, these appear to be among the most massive late type galaxies in the current epoch. They are rare objects: comparably massive galaxies today are primarily old, gas-poor, bulge-dominated systems (Kauffmann et al. 2003c).

In contrast, the compact UVLGs overlap the properties of the Lyman Break Galaxies in all respects considered in this paper (see Table 1). By definition, they have similar UV luminosities. They have sizes, surface brightnesses, UV extinctions, and implied star formation rates that all overlap those of the LBGs. They have similar stellar masses, velocity dispersions, and gas-phase metallcities as LBGs. Their rest-frame UV-optical spectral energy distributions are similar to those of LBGs. Finally, they are forming stars at a rate sufficient to form their present stellar mass in typically 1 to 2 Gigayear. The compact UVLGs are clearly systems undergoing starbursts, and a relatively low duty cycle for such bursts presumably contributes to their relative rarity today. Since the compact UVLGs do appear

[4] Kauffmann et al. (2003b) show that the SDSS spectra and images are dominated by starlight in type 2 AGN, so our methods for inferring galaxy masses, star formation rates, sizes, etc. are not significantly affected by the AGN.

similar to the LBGs, these "living fossils" may provide an opportunity for a detailed *local* investigation of the same physical processes that occurred in typical star forming galaxies in the early universe.

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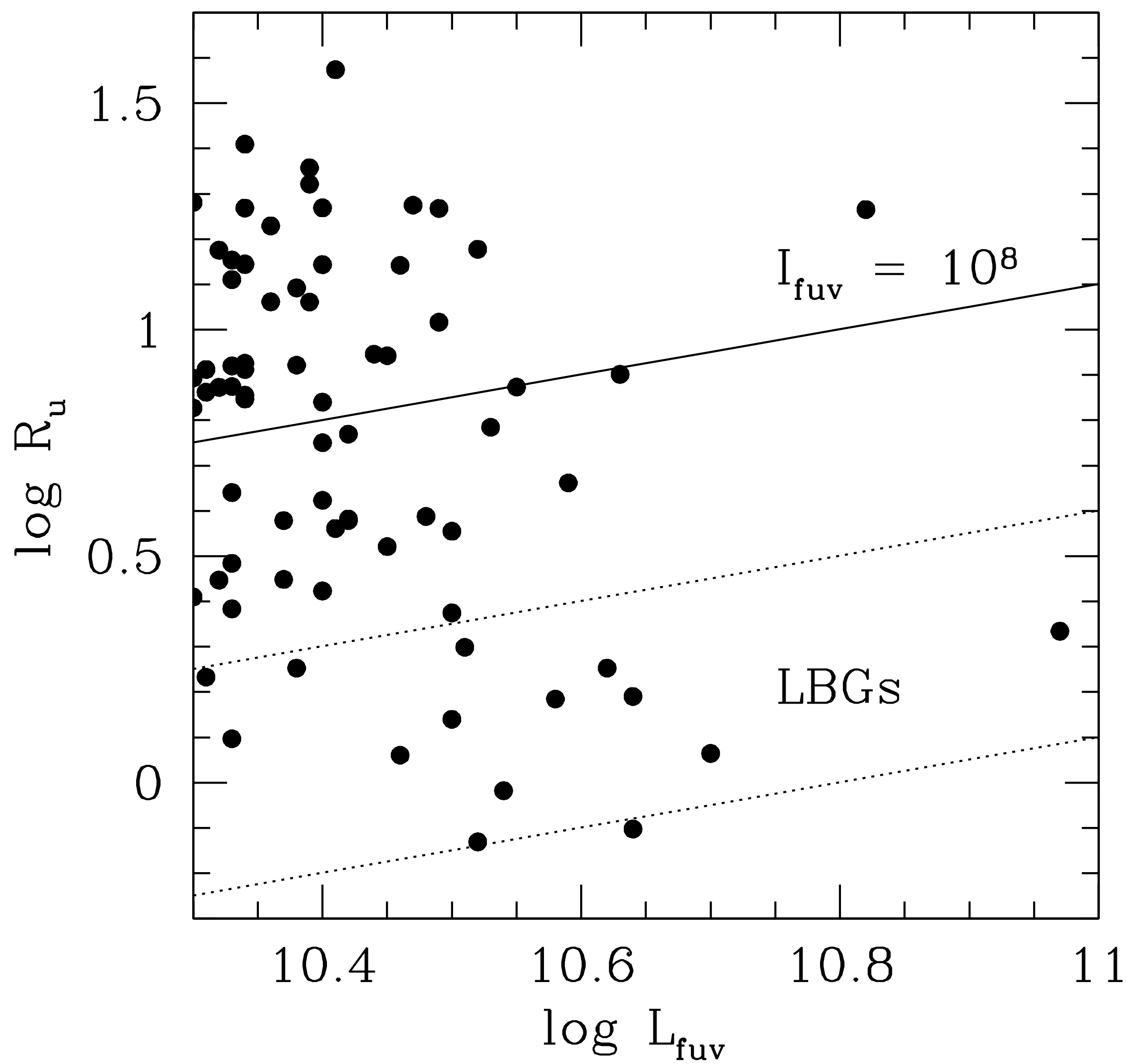

Fig. 1.— Far-Ultraviolet luminosity ($L_\odot$) *vs.* the seeing-deconvolved galaxy half-light radius measured in the SDSS u-band (kpc). We define large (compact) UVLGs as those galaxies with far-UV surface brightnesses less than (greater than) $10^8 L_\odot$ kpc^{-2} (shown by the solid line). The location of typical high-z Lyman Break Galaxies is bounded by the dotted lines.

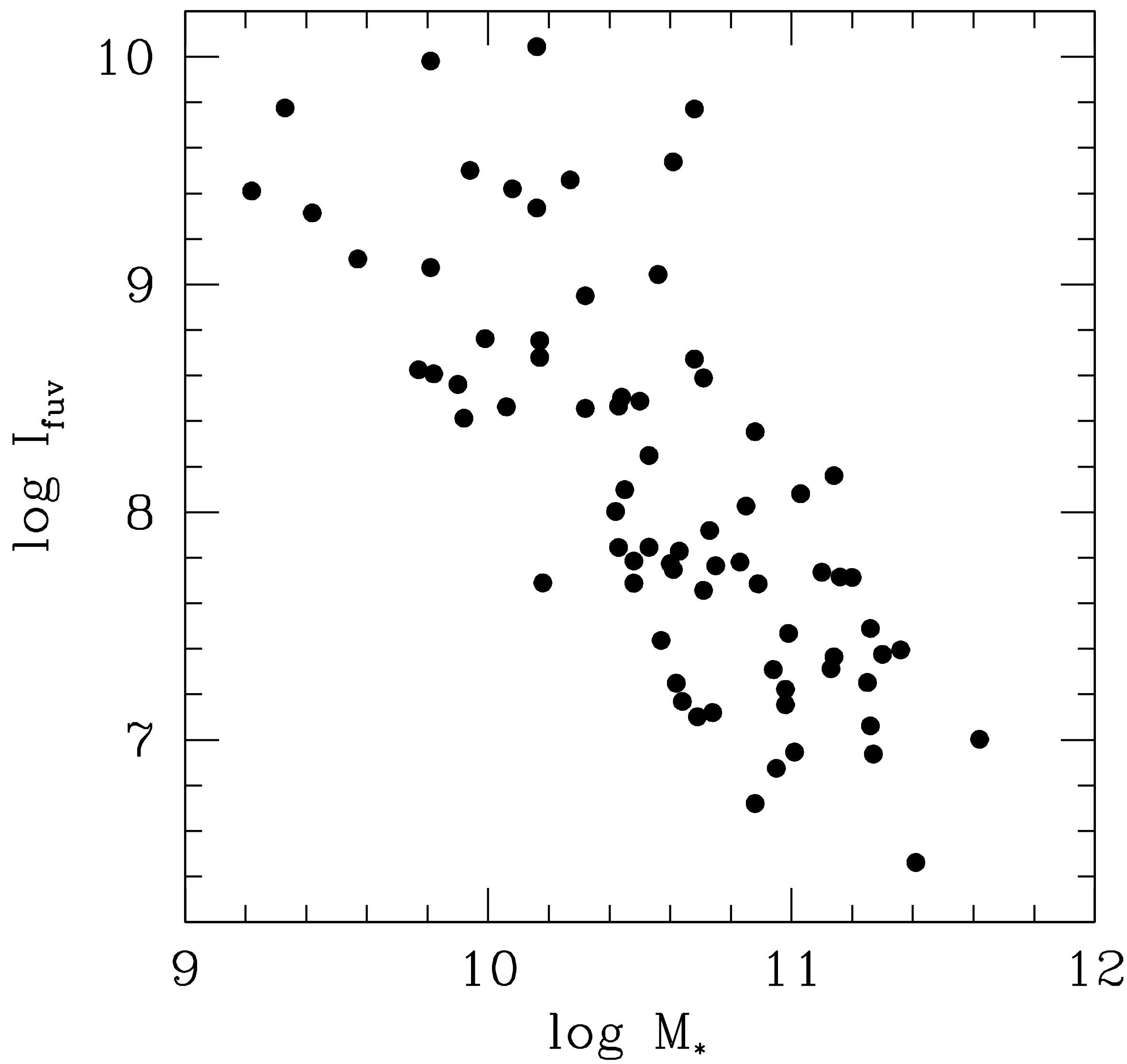

Fig. 2.— Far-Ultraviolet effective surface brightness (the mean surface brightness interior to the SDSS u-band half light radius) in units of $L_\odot$ kpc^{-2} *vs.* the stellar mass ($M_\odot$) for the UVLGs. We define large (compact) UVLGs as those galaxies with surface brightnesses less than (greater than) $10^8 L_\odot$ kpc^{-2}. The strong correlation between mass and surface brightness means that compact UVLGs are typically much less massive than large UVLGs ($\sim 10^{10}$ *vs.* $\sim 10^{11} M_\odot$ respectively). Typical Lyman Break Galaxies lie in the upper left of this plot ($log\ I_{fuv} \sim 9$ to 10 and $log\ M_* \sim 9$ to 11).

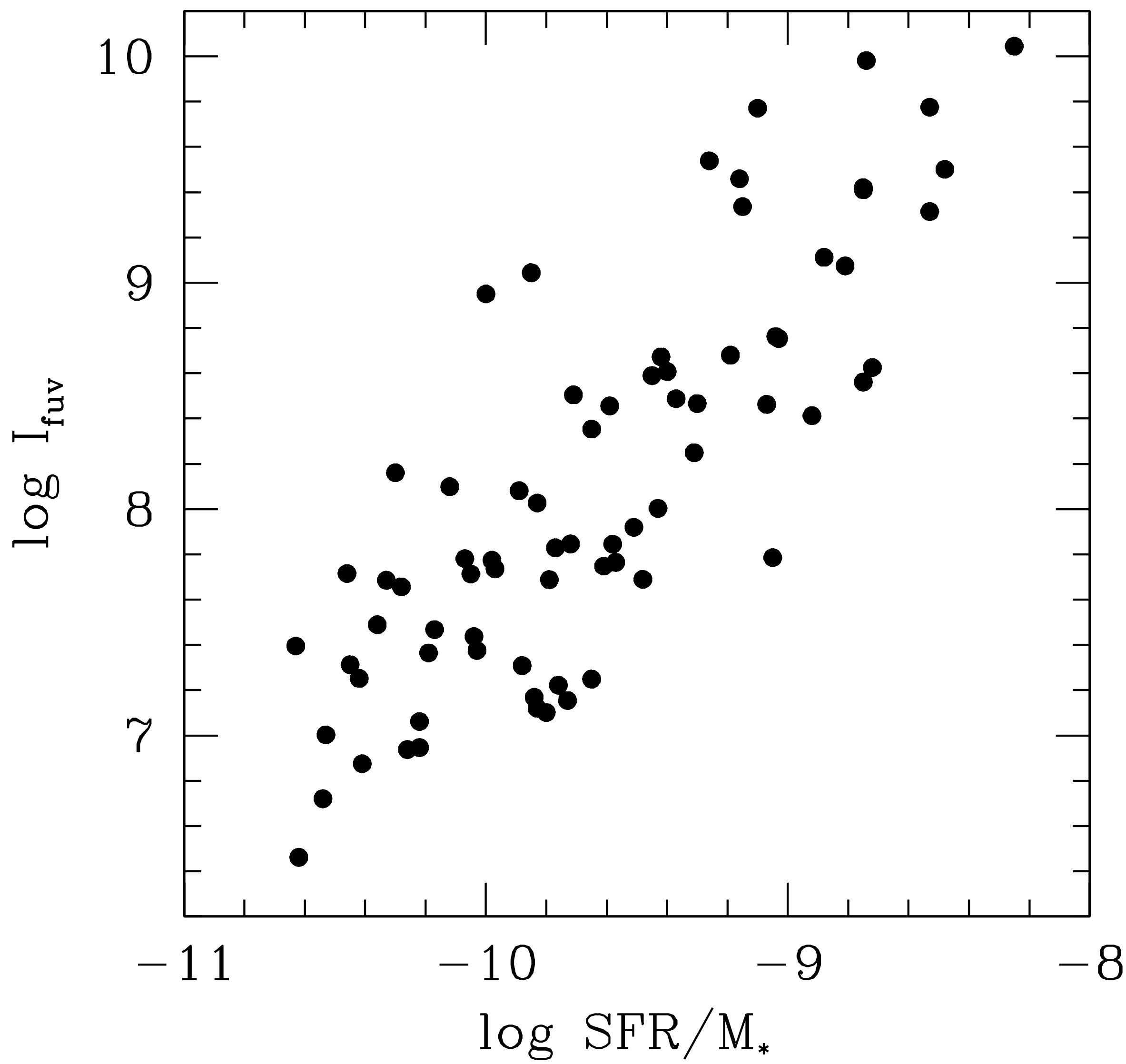

Fig. 3.— Far-Ultraviolet effective surface brightness *vs.* the star formation rate per unit mass (year^{-1}). The compact UVLGs are typically starbursts (M_*/SFR is of-order a Gigayear), while the large UVLGs are not (M_*/SFR is of-order the Hubble time). Typical Lyman Break Galaxies lie in the upper right of this plot ($log\ I_{fuv} \sim$ 9 to 10 and $log\ SFR/M_* \sim$ -9 to -8).

Table 1. Summary of Properties

Parameter (1)	Units (2)	Large UVLGs (3)	Compact UVLGs (4)	Lyman Break Galaxies (5)
$log\ L_{fuv}$	$L_\odot$	10.3 – 10.5	10.35 – 10.65	10.3 – 11.3
$log\ R50_u$	kpc	0.9 – 1.3	0.0 – 0.7	0.0 – 0.5
$log\ I_{fuv}$	$L_\odot/\mathrm{kpc}^2$	6.9 – 7.8	8.2 – 9.8	9 – 10
$log\ M_*$	$M_\odot$	10.5 – 11.3	9.5 – 10.7	9.5 – 11
$log\ M_{dyn}$	$M_\odot$	10.4 – 11.6	10.0 – 10.8	10.0 – 10.5
$log\ \mu_*$	$M_\odot/\mathrm{kpc}^2$	7.9 – 8.7	8.0 – 9.1	8.5 – 9.0
A_{fuv}	mag	0.3 – 2.0	0.6 – 2.1	1 – 3
$log\ SFR$	$M_\odot$/year	0.6 – 1.2	0.6 – 1.4	0.5 – 2.5
$log\ SFR/M_*$	year^{-1}	-10.5 – -9.5	-9.8 – -8.6	-9 – -8
$(FUV - r)$	AB mag	1.8 – 2.9	0.6 – 2.1	0.2 – 2.2
$D(4000)$	–	1.2 – 1.7	1.0 – 1.3	N/A
$12 + log\ O/H$	–	8.55 - 8.75	8.2 - 8.7	7.7 - 8.8
$log\ \sigma_{gas}$	km/sec	1.7 - 2.1	1.8 - 2.2	1.7 - 2.1

Note. — For the UVLGs, the entries in each column refer to the 10 to 90 percentile range. For the Lyman Break Galaxies, the ranges are just meant to be representative of the population at $z \sim 3$. These were extracted from Shapley et al. (2001), Papovich et al. (2001), Pettini et al (2001), Giavalisco (2002), Ferguson et al (2004), and Giavalisco (private communication). All the parameters are described in the text.